

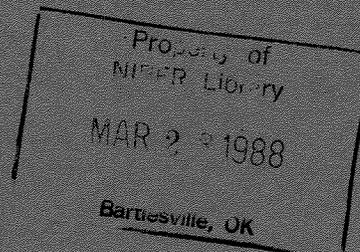
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**LABORATORY EVALUATION OF FORWARD COMBUSTION IN SUNNYSIDE  
TAR SAND**

By  
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September 1987

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For  
U. S. Department of Energy  
Office of Fossil Energy  
Morgantown Energy Technology Center  
Laramie Project Office  
Laramie, Wyoming

By  
Western Research Institute  
Laramie, Wyoming

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## SUMMARY

Three one-dimensional simulations of the in situ forward-combustion process using Sunnyside (Utah) tar sand were conducted to evaluate its effectiveness for recovering oil from the deposit. The injectant for these tests was either steam-oxygen, air-oxygen, or air. All three simulations experienced plugging of the reactor tube during the tests. Only the air test went to completion and produced 46 wt % of the bitumen as a highly upgraded oil.

The plugging problem in the tests is believed to result from the collection of a highly oxidized material in a cooler portion of the tube forming a semi-solid barrier. It is recommended that extensive thermal characterization studies be conducted on Sunnyside tar sand before further in situ studies are conducted.

The work described here substantiates the need for extensive laboratory evaluation of a recovery process before field application.

## INTRODUCTION

The Sunnyside tar sand deposit is located in east-central Utah near Price, Utah. Resource estimates of 6.1 billion barrels of bitumen make it the largest deposit in Utah. Average bitumen saturation is 50% of pore volume at an average porosity of 24%, and pay thickness ranges from 105 to 650 feet. The 8° API, low sulfur (0.7 wt %) bitumen has a reported viscosity of 100,000 cp at reservoir temperature (IOCC 1984).

Laboratory studies conducted by the Western Research Institute (WRI) have evaluated the potential of steamflood, hot-gas pyrolysis, reverse combustion, and dry- and wet-forward combustion for the in situ production of bitumen from Utah tar sands (Romanowski and Thomas 1985a-d; Johnson and Thomas 1985; Johnson et al. 1980, 1982). These studies have shown that all of the processes are effective to varying degrees for producing oil from Asphalt Ridge and Tar Sand Triangle tar sands. Based on the results of the above studies, forward combustion using steam-oxygen injection was selected as the process for further study for the following reasons: (1) the product oil quality is improved relative to steamflood produced oils, (2) the coke formed from pyrolysis of the oil exceeds fuel requirements for the process, (3) frontal velocities with steam-oxygen injection are faster than those with air injection, and (4) the plugging problems experienced with air-only combustion simulations are reduced when steam-oxygen injection is used. More detailed studies (Romanowski and Thomas 1986a and 1986b; Johnson and Romanowski 1987) of the process parameters which affect the application of forward combustion to Utah tar sands show that:

- Ignition temperature for both Tar Sand Triangle and Asphalt Ridge tar sand was 650-750°F (343-399°C).
- Coke produced from the pyrolysis of tar sand was sufficient (even for the leaner Tar Sand Triangle material) to provide thermal energy for the process.
- Using steam-oxygen injection gave higher oil yields than using straight air injection.
- Reduced fuel consumption and oxygen requirements were found in the steam-oxygen tests versus the air-combustion tests.
- The combustion-front velocity was increased in the steam-oxygen tests because of improved process efficiency.
- The product oil quality was improved with respect to the bitumen for both air and steam-oxygen combustion. The air combustion process produced better quality oil than the steam-oxygen process because the steam-produced oil in the steam-oxygen process diluted the pyrolysis-produced oil.
- The steam-oxygen tests in the richer tar sands did not experience the severe plugging problems that were characteristic of the air-combustion process.

Investigations into other tar sands and heavy oils have yielded similar results (Burger and Sahuquet 1973; Bennion et al. 1978; Ward and Ward 1985; Garon et al. 1986).

Because in situ processing studies for the Sunnyside tar sand are absent in the public literature, the studies on Tar Sand Triangle and Asphalt Ridge tar sands have provided the design basis for a series of simulation tests to evaluate the forward combustion in situ process. Conducting laboratory simulations instead of extrapolating the results from previous studies is needed in order to evaluate the combustion process efficiency and determine air or oxygen requirements. It is recognized that process parameters are specific to the hydrocarbon-matrix system and, therefore, should be determined for each reservoir using actual reservoir materials (Moss and Cady 1982; Chu 1983; Garon et al. 1986). This paper presents the results of the three forward-combustion simulations using Sunnyside tar sand.

### EXPERIMENTAL APPARATUS AND PROCEDURE

The tar sand used in this study was obtained from an outcrop at the Sunnyside deposit in Utah. This oil-wet tar sand had an initial bitumen content of 11.6 wt % with water saturation of about 0.7 wt %.

Material balance Fischer assay analyses were conducted on the Sunnyside outcrop sample to provide pyrolysis reference data for the forward-combustion tests. During the Fischer assay procedure, the tar sand sample is heated autogenously at a rate of about 1300°F/hr (720°C/hr) to a maximum temperature of 932°F (500°C). At these pyrolysis conditions, the product oil has an atomic H/C ratio of 1.69 and an API gravity of about 21. The oil yield is 70 wt % of the bitumen with 25 wt % remaining on the spent sand as residual carbon (coke).

The tube reactor shown in Figure 1 is capable of simulating the thermal recovery process of forward combustion, in addition to the processes of steam displacement, hot-gas pyrolysis, and reverse combustion. The reactor tube (3 5/16" i.d. x 32" long) is uniformly packed with approximately 18 lbs of tar sand (Romanowski and Thomas 1985a) and is vertically oriented within a series of insulated shield heaters. Auxiliary equipment includes inlet gas injection and product gas metering devices, a steam generator, a gas heater, product separation equipment, a continuous oxygen analyzer, and a gas chromatograph. The entire system is instrumented and interfaced to a data acquisition computer which records temperatures, pressures, and flow rates every five minutes.

Six internal reactor thermocouples are spaced approximately every six inches within the center of the packed tar sand to monitor the thermal front movement. These thermocouples are also electronically paired with additional internal-wall thermocouples. Each pair is connected to one of six individual temperature controllers and shield heaters. This arrangement allows the reactor tube to be operated either isothermally (preheated) or adiabatically.

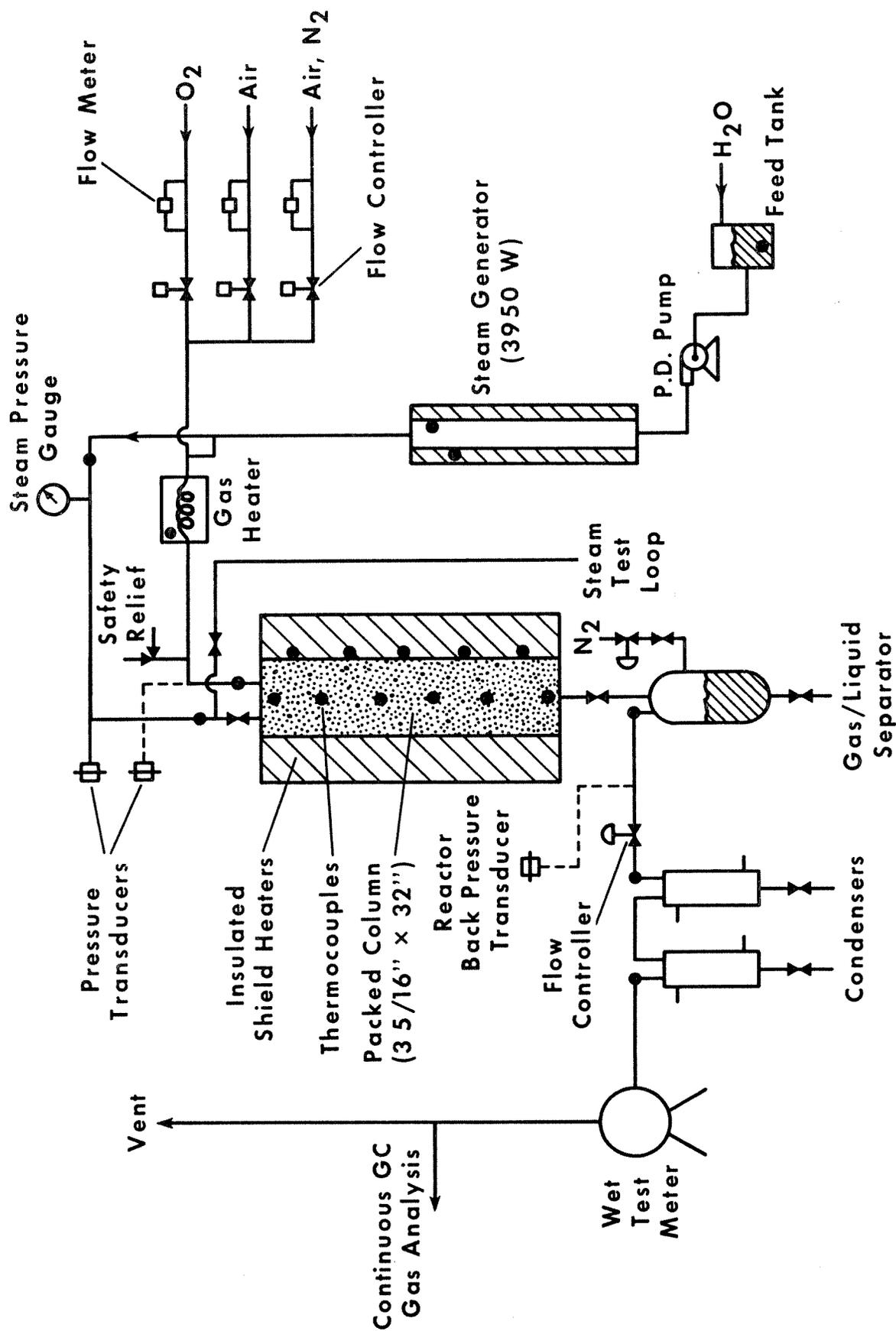


Figure 1. Tube Reactor Schematic

Air, steam, and oxygen, either separately or simultaneously, are metered into the top of the reactor. A positive displacement pump injects water through a heater to generate steam.

Product oil and water samples are collected from three knockout pots. A constant reactor back pressure can be maintained by a flow control valve at the discharge port of the initial gas and liquid separator. The middle knockout pot is chilled to 32°F (0°C) to condense process water and oil vapors. A final cold trap is maintained at -94°F (-70°C) to recover entrained oil mist. Product gas volume is measured by a wet test meter, and the gas composition is analyzed hourly by an on-line gas chromatograph. An on-line oxygen meter continuously monitors the oxygen concentration in the product gas to indicate rapid changes in the combustion process, such as those occurring during ignition.

The first simulation, FC63, was a steam-oxygen combustion test using a steam:oxygen ratio of 3.9:1. Ignition procedures for this test were the same as those used in prior steam-oxygen tests on Asphalt Ridge tar sand (Johnson and Romanowski 1987). The reactor tube was first preheated by the guard heaters to approximately 350°F (177°C) to insure bitumen mobility. Steam injection was then initiated at 33 scfh/ft<sup>2</sup> to establish and maintain a communication path within the tube. With communication established, the top guard heater was increased to 750°F (399°C) followed by oxygen injection at 8.5 scfh/ft<sup>2</sup>. Properties of the packed tube and run conditions are given in Table 1. With adiabatic reactor conditions implemented, the heated injectant in conjunction with exothermic oxidation reactions gradually increased the temperature in the top 5-6 inches of the tar sand bed to between 650 and 750°F (343 and 399°C). At these temperatures, the tar sand ignited and the oxygen in the product gas rapidly decreased to zero. Injection pressure was generally less than 60 psig with no back pressure on the reactor during the ignition period. With the inception of combustion, the injection pressure slowly increased to 180 psig and then rapidly increased to 900+ psig at a constant injection rate (Figure 2). After several unsuccessful attempts to reduce the injection pressure in the tube, the test was terminated.

The second simulation (FC64) was conducted as an enriched-air combustion test with no steam injection (Table 1). Ignition was accomplished by first preheating the entire tube with the guard heaters to ~350°F (~177°C) and then increasing the temperature at the injection end of the tube with the guard heater to 700-750°F (371-399°C) while injecting enriched air containing an oxygen concentration of 22% by volume. Rapid ignition of the tar sand occurred with these conditions at an injection pressure less than 60 psig. As in the prior test, FC63, the injection pressure first slowly increased and then rapidly increased. All attempts to reduce the injection pressure failed, and the test was terminated.

The third and final simulation, FC65, was an air only, dry-combustion test with no preheating prior to ignition. Ignition was accomplished by raising the temperature at the injection end of the tube to 700-750°F (371-399°C) with simultaneous air injection (Table 1). All

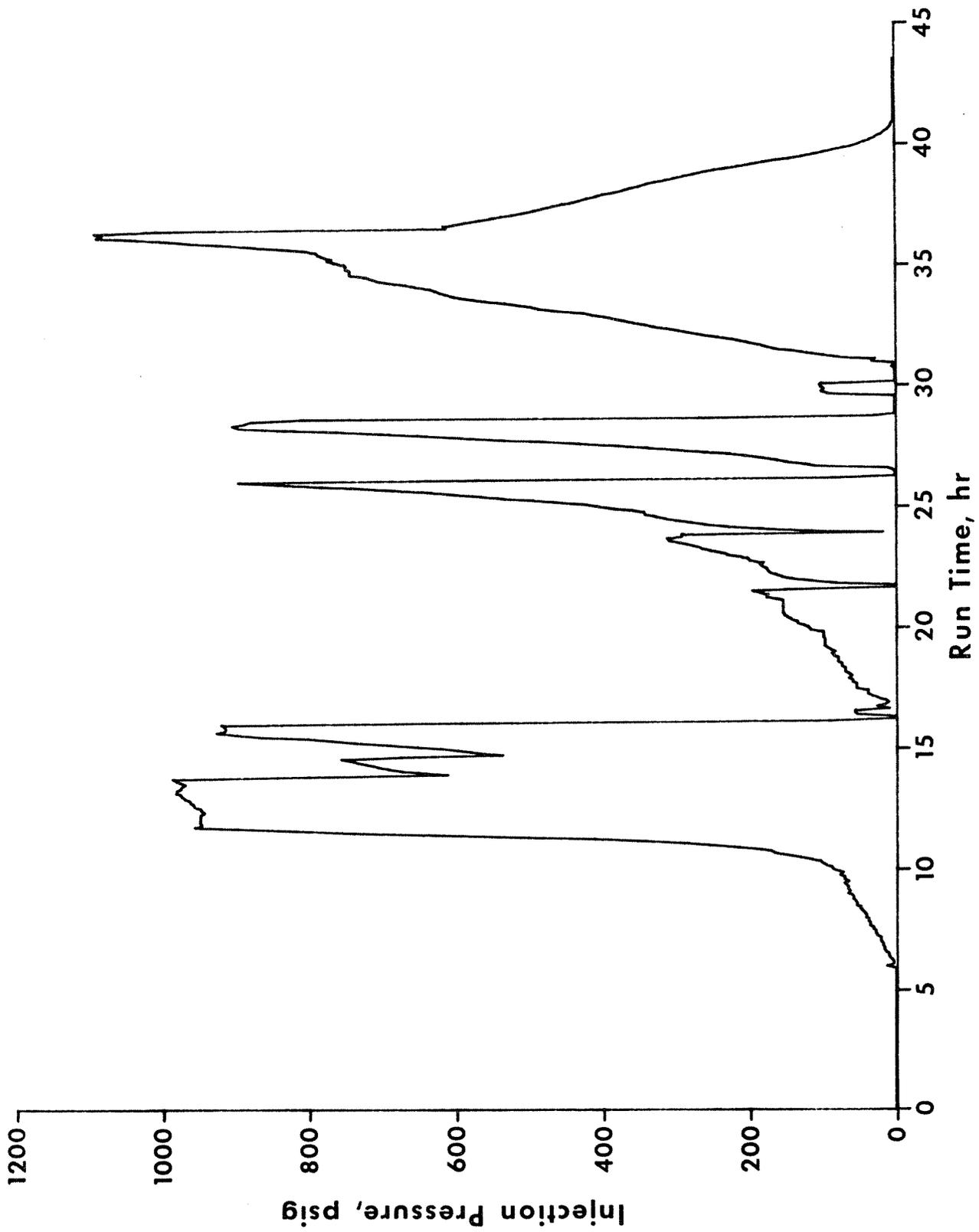


Figure 2. Injection Pressure for Steam-Oxygen Forward Combustion Simulation Using Sunnyside Tar Sand

**Table 1. Experimental Conditions and Results for  
Sunnyside Combustion Tests**

	FC63	FC64	FC65
Permeability, darcy	1.2	1.0	1.3
Porosity, %	41	39	40
Oil Saturation, % PV	51	55	54
Injection flux, scfh/ft <sup>2</sup>			
Steam	33	--	--
Oxygen	8.5	1.4	--
Air	--	64.3	79.2
Steam-Oxygen Ratio	3.9:1	--	--
Nitrogen-Oxygen Ratio	--	3.4:1	3.7:1
Cumulative Injectant			
Steam, PV	0.55	--	--
Oxygen, scf	11.53	0.93	--
Air, scf	--	58.15	76.87
Maximum Injection Pressure, psig	1000	1000	1000
Peak Combustion Temperature, °F	1630	1670	1760
Oil Yield, wt % Initial Bitumen	30.6	22.5	46.2
Time to Plug from Start of Oxidant Injection, hrs	5.7	5.0	4.0

other guard heaters were set in the adiabatic mode. The injection pressure during this test followed the pattern of the previous tests. However, the plugging problem was overcome by increasing the temperature in the lower parts of the reaction tube to 450-500°F (232-260°C). The test was terminated when oxygen breakthrough occurred at the production end of the reactor tube.

Product liquid samples from all tests were separated into oil and water by centrifugation. A sample of the original bitumen was also obtained by Soxhlet extraction of the tar sand with toluene followed by pyridine.

Selected chemical and physical properties of the bitumen and product oil were determined by ASTM procedures (Table 2). Analyses included carbon, hydrogen, nitrogen, sulfur, API gravity, viscosity, molecular weight, and the distillation range. Mineral and organic carbon analyses were also performed on raw and spent sand samples. These

**Table 2. Chemical and Physical Properties of Original Bitumen and Produced Oils (Sunnyside)**

	Original Bitumen	FC63 <sup>a</sup>	FC64 <sup>a</sup>	FC65 <sup>a</sup>
Elemental Analysis, wt %				
Carbon	86.3	86.1	87.0	86.3
Hydrogen	11.7	12.8	12.1	12.3
Nitrogen	0.9	0.2	0.5	0.9
Sulfur	0.5	0.5	0.4	0.4
Oxygen (by difference)	0.6	0.4	TR	0.1
H/C Ratio	1.63	1.78	1.67	1.71
Molecular Weight	680	265	250	305
Gravity, °API	10.4	25.5	22.6	21.6
Distillation Data, wt %				
0-600°F	2.9	--	40.7	37.3
600-1000°F	28.8	--	59.3	62.7
>1000°F	68.3	--	0	0
Viscosity, cp				
60°F	--	26.2	--	--
100°F	1,600,000	--	11.7	36.9
140°F	140,000	--	6.1	15.4
195°F	1,300	--	3.5	7.0

<sup>a</sup> Produced oil properties are for the composite produced oil and include all produced light hydrocarbons from venting procedures.

properties provided data for evaluating the recovery process and the extent of product oil upgrading.

After removing the spent tar sand from the reactor tube, the concentration of residual bitumen and coke (toluene insoluble organics) on the spent sand was measured. Sections of the core representing 25 wt % of the total spent sand were analyzed. The residual bitumen was determined by Soxhlet extraction with toluene. The coke was determined by difference after the extracted sample was burned in a muffle furnace at 900°F (482°C). The composition and volume of the product gas and the total organic carbon content of the product water were also measured for material balance calculations.

## RESULTS AND DISCUSSION

Three simulations of the in situ forward-combustion process were conducted on a Sunnyside tar sand containing 11.6 wt % bitumen. The simulations used steam-oxygen (FC63), air-oxygen (FC64), or air (FC65)

as the injectant (Table 1). Vigorous combustion was established in all three simulations as indicated by the complete utilization of the injected oxygen and the production of carbon monoxide and carbon dioxide. Ignition temperatures were in the range of 650 to 700°F (343 to 371°C) for all tests.

The first simulation with steam-oxygen experienced severe plugging of the reactor tube within six hours after establishing oxygen injection. To resolve the plugging problem, the injection end of the reactor tube was vented through the production system to relieve the high pressure and, therefore, flash any condensed water and oil which may have been causing a liquid block in the tube. This venting of the injection end was attempted several times (Figure 2). With each venting, water (steam), light liquid hydrocarbons indicated by 100% distillate products (Table 2), and hydrogen-rich gas (Table 3) indicative of bitumen cracking and combustion of light oils were produced, and only limited flow through the tube was noted when injection was resumed.

**Table 3. Product Gas Composition (Dry Basis) from Sunnyside Combustion Tests**

	FC63	FC64	FC65
Injected Gas	Steam-O <sub>2</sub>	Air-O <sub>2</sub>	Air
Product Gas Composition, vol % <sup>a</sup> (N <sub>2</sub> and Ar Free)			
H <sub>2</sub>	10.1	7.2	7.6
CO	2.8	11.8	10.9
CO <sub>2</sub>	66.7	70.6	59.7
CH <sub>4</sub>	13.8	8.1	12.7
C <sub>2</sub> =	3.3	0.9	3.5
C <sub>2</sub>	0.6	0.2	1.0
C <sub>3</sub> =	0.6	0.3	1.7
C <sub>3</sub>	0.7	0.4	1.7
C <sub>4</sub>	0.9	0.4	1.1
H <sub>2</sub> S	0.5	0.1	0.1

<sup>a</sup> Product gas composition includes all gases vented from the injection end through the production system.

To evaluate the plugging problem in FC63, FC64 was operated as an enriched-air, dry-combustion simulation (Table 1). Enriched air was selected over steam-oxygen to minimize any effect that steam or its condensation may have on the plugging problem. Within five hours of establishing oxidant injection, the same plugging problem experienced in FC63 was again occurring. Neither pressure venting of the injection end of the reactor tube nor increasing the temperature of the entire tube to approximately 450°F (232°C) overcame the plugging problem.

With the elimination of steam or its condensation as the main cause of plugging, investigating the cause of the plugging was directed to the spent sand pack and the residual oil in it. A sample of the residual oil in the zone ahead of the pyrolysis zone was extracted from the spent sand. The oil saturation had increased from the original 11.6 wt % to 14.6 wt %. The viscosity of this residual oil at 195°F (91°C) was 207,000 cp, a 150-fold increase over the original bitumen viscosity of 1,300 cp at the same temperature. This significant change in viscosity was believed to be caused by one or more of the following mechanisms: (1) polymerization of the bitumen, (2) formation of oxidation products which typically increase viscosity, a condition similar to the situation with aged asphalts, or (3) the devolatilization of the bitumen, a condition similar to the "topping" of petroleum to prepare asphalts. Solubility screening on the residual oil showed that significant chemical condensation did not occur to form resinous polymers. Linear polymerization probably did not occur, as shown by a small increase in molecular weight from 680 to 1000. Functional group analysis as described by Petersen (1975) showed that oxidation did occur to an extent greater than observed in typical highly-aged road construction asphalts.

The third simulation was conducted as a dry forward-combustion test with air as the only injectant and no preheating of the tube prior to oxidant injection. Within four hours of the start of the test and ignition, the injection pressure began to mirror that of the previous two simulations. However, increasing the temperature with the guard heaters in the zone immediately ahead of the combustion and pyrolysis zones to 450-500°F (232-260°C) reduced the plugging problem to a point where the test could be conducted at a constant injection rate and pressure. This process of increasing the temperature in the zone immediately ahead of the combustion and pyrolysis zone was repeated throughout the entire test. This test produced 46% of the bitumen (Table 1) as a highly upgraded oil (Table 2) by establishing and maintaining a sharp combustion front throughout the tube. However, even though the yield and the product oil quality are good, extrapolating this type of process to a field test is not practical at this time.

## CONCLUSIONS

The following conclusions have been drawn from the results of these one-dimensional simulations of forward combustion using tar sand from the Sunnyside deposit in Utah.

- Sunnyside tar sand can be successfully ignited at a temperature of 650 to 700°F (343 to 371°C).

- Plugging during forward combustion will be a problem in Sunnyside tar sand. However, development of an ignition and operational procedure that produces a sharp combustion front may eliminate the plugging problem, which is believed to be caused by oxidized products ahead of the combustion front.
- Extensive studies need to be done on the thermal behavior of the Sunnyside bitumen-sand system before any further in situ thermal recovery studies are warranted.
- Laboratory simulations must be conducted prior to the field application of any process to a given resource because extrapolation of results from studies on other hydrocarbon-sand systems will not necessarily identify all processing parameters or problems.

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